REPORT

TO THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ANNUAL STATUS REPORT
(Includes Semiannual Status Report #4)

for

GRANT NAGW-533

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

Paul G. Steffes, Principal Investigator

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Submitted by

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often lead to significant misinterpretation of available opacity data. Steffes and Eshleman (1981) showed that under environmental conditions corresponding to the middle atmosphere of Venus, the microwave absorption due to atmospheric SO_2 was 50 percent greater than that calculated from Van Vleck-Weiskopff theory. Similarly, the opacity from gaseous H_2SO_4 was found to be a factor of 7 greater than theoretically predicted for conditions of the Venus middle atmosphere (Steffes and Eshleman, 1982). The recognition of the need to make such measurements over a range of temperatures and pressures which correspond to the periapsis altitudes of radio occultation experiments, and over a range of frequencies which correspond to both radio occultation experiments and radio astonomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements.

In the initial year of Grant NAGW-533 (i.e., February 1, 1984 through January 31, 1985), this facility was developed, and then operated, in order to evaluate the microwave absorbing properties of gaseous sulfuric acid (H_2SO_4) at 13.4 and 3.6 cm wavelengths, under Venus atmospheric conditions. The

results were then applied to measurements from Mariner 5, Mariner 10, and Pioneer-Venus Radio Occultation experiments, to determine abundances of gaseous sulfuric acid in the Venus atmosphere, with accuracies exceeding those achieved with in-situ instruments. Measurements of the microwave properties of the vapors accompanying liquid H_2SO_4 also resulted in more accurate estimates of the vapor pressure behavior of sulfuric acid, which are critical for modeling the behavior and structure of the Venus atmosphere. The results of this work are being published in a paper entitled, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Vapor under Simulated Conditions for the Middle Atmosphere of Venus," in the journal, Icarus (Steffes, 1985).

During the first six months of the current grant year, our work concentrated on making laboratory measurements of the microwave absorption from gaseous H_2SO_4 at wavelengths from 1 to 22 cm under simulated Venus conditions. Additional measurements of the vapor pressure behavior of sulfuric acid were also made. During the second half of this year, we have applied these results to radio astronomical observations of Venus which have been made in the same wavelength range, in order to better model the structure of H_2SO_4 and SO_2 abundance in the Venus atmosphere, and to resolve temporal variations of their abundances on a planet-wide basis. The results of this effort have been especially rewarding in that the unique frequency and pressure dependences measured for the absorption from gaseous H_2SO_4 in these wavelength ranges has finally explained what were thought to be inconsistencies between absorption measurements of the Venus atmosphere at 13.3 and 3.6 cm wavelengths and those obtained in the 1 to 3 cm wavelength range. We describe these effects, and the resulting limitations they place on abundances of gaseous H_2SO_4 and SO_2 in

the Venus atmosphere, in a paper entitled, "Evaluation of the Microwave Spectrum of Venus in the 1.3 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," which is being prepared for submission to Astrophysical Journal. In addition, we have completed the process of redesigning and refitting the laboratory system so as to permit measurements of the microwave absorptivity of ammonia (NH_3), methane (CH_4), and other potential microwave absorbers under simulated conditions for the outer planets (Jupiter, Saturn, Uranus, and Neptune). In May, a paper entitled, "Laboratory Measurements of Microwave Absorption from Gaseous Atmospheric Constituents under Conditions for the Outer Planets," was presented at the Conference on the Jovian Atmospheres, held at the Goddard Institute for Space Studies in New York, in which feedback from other experimenters was sought in order to optimize the yield from our outer planets simulations. (See Appendix 1.) This feedback helped significantly in our design of the outer planets atmospheric simulator.

Our plans for future work includes, as time and resources permit, further analysis and application of our laboratory results for the microwave absorption from gaseous H_2SO_4 in the Venus atmosphere. Our long term goal would be a detailed analysis of available multi-spectral microwave opacity data from Venus including data from the Pioneer-Venus Radio Occultation experiments and earth-based radio and radar astronomical observations, such as the kinds which have been performed at the NRAO Very Large Array (VLA) and at stations in the Deep Space Network (DSN). This would provide a chance to determine both spatial and temporal variations in the abundances of both H_2SO_4 and SO_2 in the Venus atmosphere. However, our most immediate priority for the next grant year will be completion of the measurement of the microwave (1.3 to 27 GHz)

opacity of H_2, NH_3, and CH_4 under simulated conditions for the outer planets. We likewise would hope to be able to pursue a program of analysis and application of these results to microwave data for the outer planets such as Voyager Radio Occultation experiments and earth-based radio astronomical observations.

II. THE GEORGIA TECH RADIO ASTRONOMY AND PROPAGATION (R.A.P.) FACILITY

The basic configuration of the planetary atmospheres simulator developed at Georgia Tech for use in measurement of the microwave absorptivity of gases under simulated conditions for planetary atmospheres is described at length in the first Annual Status Report for Grant NAGW-533 (February 1, 1984 through January 31, 1985). It is also discussed at length in Steffes (1985). The major new addition made to the laboratory apparatus is a microwave resonator capable of making absorptivity measurements in the 8 to 27 GHz range (1.1 to 3.7 cm wavelengths). This significantly extends the operating range beyond the previous 1.3 to 8.5 GHz (3.6 to 22 cm) operating range. As shown in Figure 1, the system was initially configured so as to be used in measuring microwave absorption (1.3 to 27 GHz) from gaseous H_2SO_4 under simulated conditions for the middle atmosphere of Venus (total pressures from 1 to 6 atm, temperatures from 500 to 575 K).

Adding a resonator capable of operating in the 8 to 27 GHz frequency range was more difficult than expected, especially considering the high temperatures and pressures involved. It was decided to use coaxial cable to interconnect the high frequency resonator to the microwave instrumentation, since hermetically-sealed coaxial feed-through connectors were available which would allow operation to 30 GHz while still maintaining the pressure integrity of the chamber. The type of coaxial cable required for the higher frequency

resonator was different from that used in the 1.3 to 8.5 GHz range, in that a solid metallic jacket is required to prevent signal leakage. as opposed to the metallic braid used in lower frequency cables. Unfortunately, even when high-temperature solder was used, connector failure occurred for these cables at temperatures above 500 K. This was due to the extrusion of the PTFE (Teflon) dielectric material within the cable placing mechanical stresses on the connectors. As a result, a limited production air-dielectric cable was obtained which employs a PTFE spline to space the center conductor from the solid metallic outer conductor. The connectors for this specialized cable have been difficult to obtain since special production runs (and accompanying set-up charges) are usually required. Fortunately, we were able to combine the production of our connectors with those from other customers so as to avoid these charges. The result has been a system capable of successfully measuring the microwave absorption from gaseous H_2SO_4 in a CO_2 atmosphere at wavelengths from 1.2 to 22 cm, at pressures from 1 to 6 atmospheres, and at temperatures from 500 to 570 K. (Lower temperatures can, of course, be achieved but the resulting gaseious H_2SO_4 abundance would be too small so as to provide measurable absorptivity.)

The pressure vessel and its accompanying resonators are designed to be usable over an extremely wide range of temperatures. The extremely high temperatures (up to 600 K) developed for the Venus atmosphere simulations by the oven/temperature chamber (see Figure 1) can be replaced by extremely low temperatures created by a freezer/temperature chamber for simulations of the outer planets, as shown in Figure 2. Such a freezer has been procured for use in such measurements. The unit, a Revco/Rheem ULT-7120D, has an internal volume of 193 liters (which is capable of containing the pressure vessel with

resonators), and is capable of maintaining temperatures as low as 150 K. Since access to the freezer is through the top of the unit, a special lifting frame and pulley system has been constructed which allows easy movement of the pressure vessel and accompanying resonators in and out of the freezer. Another critical issue has been the behavior of sealing structures such as gaskets or O-rings. We have found that at low temperatures, materials such as teflon or viton become too brittle to be used as gaskets. Thus we have tested alternate materials for use in this application. The result is a system capable of measuring microwave absorption from 1.3 to 27 GHz (1.1 to 22 cm wavelength) at pressures to 8 atmospheres and at temperatures as low as 150 K. The minimal measurable absorption absorptivity, or sensitivity, for this system when operated at 170 K is shown in Figure 3, as a function of frequency.

Another more critical limitation on how low the temperatures can be taken (while still being able to measure microwave absorption) is the saturation vapor pressure of the gas being tested. As shown in Table 1, the lowest temperature for which sufficient quantities of gaseous NH_3 would still exist so that the microwave absorption in an H_2 atmosphere would be measurable would be approximately 155 K.

A final critical issue which greatly affects the use of the simulator in outer planets simulations is the use of hydrogen (H_2) at pressures reaching 8 atmospheres. In previous simulations, small leakages from the pressure vessel presented little or no danger to the experimenters. The use of hydrogen will require a special set of procedures and a special ventilation system to be used. Initial pressure tests of the system, as configured for outer planets simulation, are currently being conducted with nitrogen (N_2). Not

only is this a safer way to test the system, but it also allows measurement of the collisional microwave absorption from N_2, which may be the source of the 3.6 cm (8.4 GHz) opacity detected by Voyager 1 radio occultation studies of the Titan atmosphere. (See Lindal et al., 1985.) It is noteworthy that funding for laboratory safety equipment needed in making such measurements has been provided by the Georgia Institute of Technology in support of planetary atmospheres research at Georgia Tech.

III. RESULTS OF LABORATORY MEASUREMENTS AND THEIR APPLICATION

Our goal for the first six months of the current grant year was to complete laboratory measurements of the microwave absorption from gaseous H_2SO_4 in the 1.2 to 22 cm wavelength range, under simulated conditions for the middle atmosphere of Venus, and to obtain additional measurements of the vapor pressure behavior of gaseous H_2SO_4 above liquid sulfuric acid. The additional vapor pressure measurements made have been consistent with the vapor pressure expression derived from earlier data. Our measured results for the microwave absorption from gaseous H_2SO_4 in a CO_2 atmosphere at 575 K are shown in Figure 4. The data points presented are for an H_2SO_4 mixing ratio of 0.4 percent at total pressures up to 6 atmospheres. Best-fit curves for the absorption spectra from 1.3 GHz (22.5 cm) to 25 GHz (1.2 cm) at pressures of 6 atm and 1 atm are also shown. Inspection of these results reveals three major results.

The first major result has been the extremely low absorptivity observed in the 1.2 to 1.8 cm wavelength range. For example, measurements made at 21.63 GHz (1.38 cm wavelength) show an opacity for a .36% mixture of gaseous H_2SO_4 in a CO_2 atmosphere (with a total pressure of 6 atmospheres and

temperature of 570 K) of less than 9 dB/km. This is far below the opacity predicted by using previous measurements at 2.2 GHz and 8.4 GHz and assuming a simple f^2 dependence such as exhibited by SO_2 and CO_2. In fact, this even implies that using the measured frequency dependences for the microwave absorption from H_2SO_4 in a CO_2 atmosphere in the 2.2 to 8.4 GHz range to predict absorption at 21.6 GHz (1.38 cm wavelength) would result in overstating the absorption at 1.38 cm by at least a factor of 2.

Such behavior implies that the contribution of gaseous H_2SO_4 to the overall non-CO_2 opacity inferred from radio astronomical observations at the 1.35 cm is minimal. Such a result is not surprising in light of the calculations done by Janssen and Klein (1981) which attribute nearly all of the non-CO_2 opacity at 1.35 cm in the Venus atmosphere to SO_2. This behavior is likewise consistent with the calculated H_2SO_4 resonance frequencies computed by Poynter. (R. Poynter, J.P.L., personal communication. Note that the results of the resonance calculations are shown in Cimino, 1982.) These calculations are based on rotational constants computed using measurements of H_2SO_4 resonances in the 60 to 120 GHz range by Kuczkowski et al. (1981). It is significant that there is a notable absence of H_2SO_4 resonances in the 15 to 30 GHz frequency range, which would be consistent with our measurements. A computation of the microwave spectrum from H_2SO_4, made by Allen, which is presented in Cimino (1982), showed significantly more absorption from H_2SO_4 in this same frequency range than we have actually measured. This can be explained by the fact that a pressure-broadened linewidth parameter of 7.2 MHz was assumed to H_2SO_4 in a CO_2 atmosphere. It appears that using a smaller broadening parameter will result in a spectrum which will be consistent with our measurements.

The second major result has been the discovery of a peak in the absorptivity from gaseous H_2SO_4 at a wavelength of approximately 2.2 cm, even at pressures as high as 6 atm. This does a lot to explain why observations of the Venus brightness temperature at 2 cm (495 K--from Pollack and Morrison, 1970), which were initially felt to be inconsistent with measurements at 1.35 cm (474 K--from Muhleman et al., 1979), are indeed consistent, because there is at least one absorber whose opacity decreases with increasing frequency, in that wavelength range. In fact, we have developed a model for the microwave emission spectrum of Venus, using our laboratory results for gaseous H_2SO_4, and previous results for SO_2 and CO_2 which provides a better fit to the ensemble of Venus microwave observations than any model yet proposed. We are currently preparing a paper to be submitted to The Astrophysical Journal, which will present this model.

The third major result has been the low absorptivity measured at 22.3 cm. This is important since the well known problem of the falloff of brightness temperatures at wavelengths longward of 20 cm (see, for example, Muhleman et al., 1979) is still unsolved, and might have been explained by a large opacity from a gaseous constituent. Our negative result indicates that no atmosphere constituent can be responsible for this effect.

Thus, as can be seen in Figure 5, our laboratory measurements indicate that while radio occultation measurements of 13 and 3.6 cm, and radio astronomical measurements at wavelengths longer than 2 cm, measure absorption which is predominated by gaseous H_2SO_4; opacity measured by radio astronomical observations in the 1 to 2 cm wavelength range is predominated by SO_2 at higher altitudes, and by CO_2 at lower altitudes.

IV. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

At the beginning of the current grant year, a paper was completed and revised for publication in Icarus, describing results and applications of experiments performed during the first year of the grant (P. G. Steffes, 1985, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Vapor under Simulated Conditions for the Middle Atmosphere of Venus.") In May, a paper was presented at the Conference on Jovian Atmospheres, at the Goddard Institute for Space Studies (New York) entitled, "Laboratory Measurements of Microwave Absorption from Gaseous Atmospheric Constituents under Simulated Conditions for the Outer Planets." (See Abstract, Appendix 1.) This paper described our plans and capabilities for simulating outer planets atmospheres and measuring microwave properties of those atmospheres. Much positive feedback was received with regard to the need for such measurements, and discussions were held with I. de Pater of UC/Berkeley and A. Kliore of JPL regarding application of such data to radio astronomical observations, and Galileo probe measurements, respectively. Contact with both is expected to continue as the measurements are made. Contacts have also been maintained with groups at the Stanford Center for Radar Astronomy (V. Eshleman, director), and JPL (Drs. Michael J. Klein and Samuel Gulkis). We have also had discussions with members of the Galileo Cloud Particle Size Spectrometer Team with regards to allowing the use of our simulator for testing of certain devices.

In August, an Invited Paper was presented at the International Association of Meteorology and Atmospheric Physics (IAMAP) Assembly (August 12, 1985) entitled, "Microwave Absorption from Cloud-Related Gases in Planetary

Atmospheres," which summarizes our work over the past 2 years and its applications. In addition, a paper was presented at the October meeting of the Division of Planetary Sciences of the American Astronomical Society (DPS/AAS) on the complete microwave spectrum of H_2SO_4 in a CO_2 atmosphere (from 1.2 to 22 cm) and its application to understanding the microwave emission spectrum from Venus (abstract attached as Appendix 3). The response from this presentation was extremely strong, from both the radar community as well as from radio astronomers. Dr. T. W. Thompson of JPL expressed a strong interest in the work and results and suggested cooperation on a Pioneer-Venus related project involving analysis of radar data. Dr. James B. Garvin of NASA-Goddard expressed strong interest in our results with regard to his interaction with the Soviet *Vega* mission to Venus. He was especially interested in our results for gaseous H_2SO_4 abundances, since gaseous H_2SO_4 was detected by the Vega probes. He was also interested in our abilities to make microwave measurements under simulated Venus conditions to support the Venus Radar Mapper program and similar Soviet synthetic aperture radar programs.

It should be noted that travel funds for all of the conferences and meetings attended were provided by the State of Georgia and the Georgia Institute of Technology, in support of planetary atmospheres research at Georgia Tech. We have also maintained contact with our congressional delegation, keeping them aware of our work, and the need for continued support to the solar system exploration program. (See Appendix 2.)

V. CONCLUSION

During the current grant year (February 1, 1985 through January 31, 1986) we have completed measurements of the microwave absorption from gaseous H_2SO_4 in the 1.2 to 22.3 cm wavelength range, as well as having applied results from earlier measurements at 3.6 and 13.4 cm wavelengths to microwave absorptivity data from radio occultation measurements at those wavelengths, in order to derive abundance profiles for gaseous H_2SO_4, SO_2, and CO_2.

Currently, we are completing the outer planets simulator construction, and beginning some preliminary measurements of the microwave absorption from nitrogen (N_2) to simulate Titan. In the next grant year we hope to measure absorption from ammonia (NH_3) and methane (CH_4) in a hydrogen atmosphere (H_2) in order to simulate Jovian atmospheres. We will likewise continue work on the application of our newly derived absorptivity spectra to a wide range of radio astronomical data.

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Steffes, P. G. and Eshleman, V. R. (1982). Sulfuric acid vapor and other cloud-related gases in the Venus atmosphere: abudances referred from observed radio opacity. Icarus 51, 322-333.

Steffes, P. G. (1985). Laboratory measurements of the microwave opacity and vapor pressure of sulfuric acid under simulated conditions for the middle atmosphere of Venus. Icarus, in press.

VII. KEY FIGURES

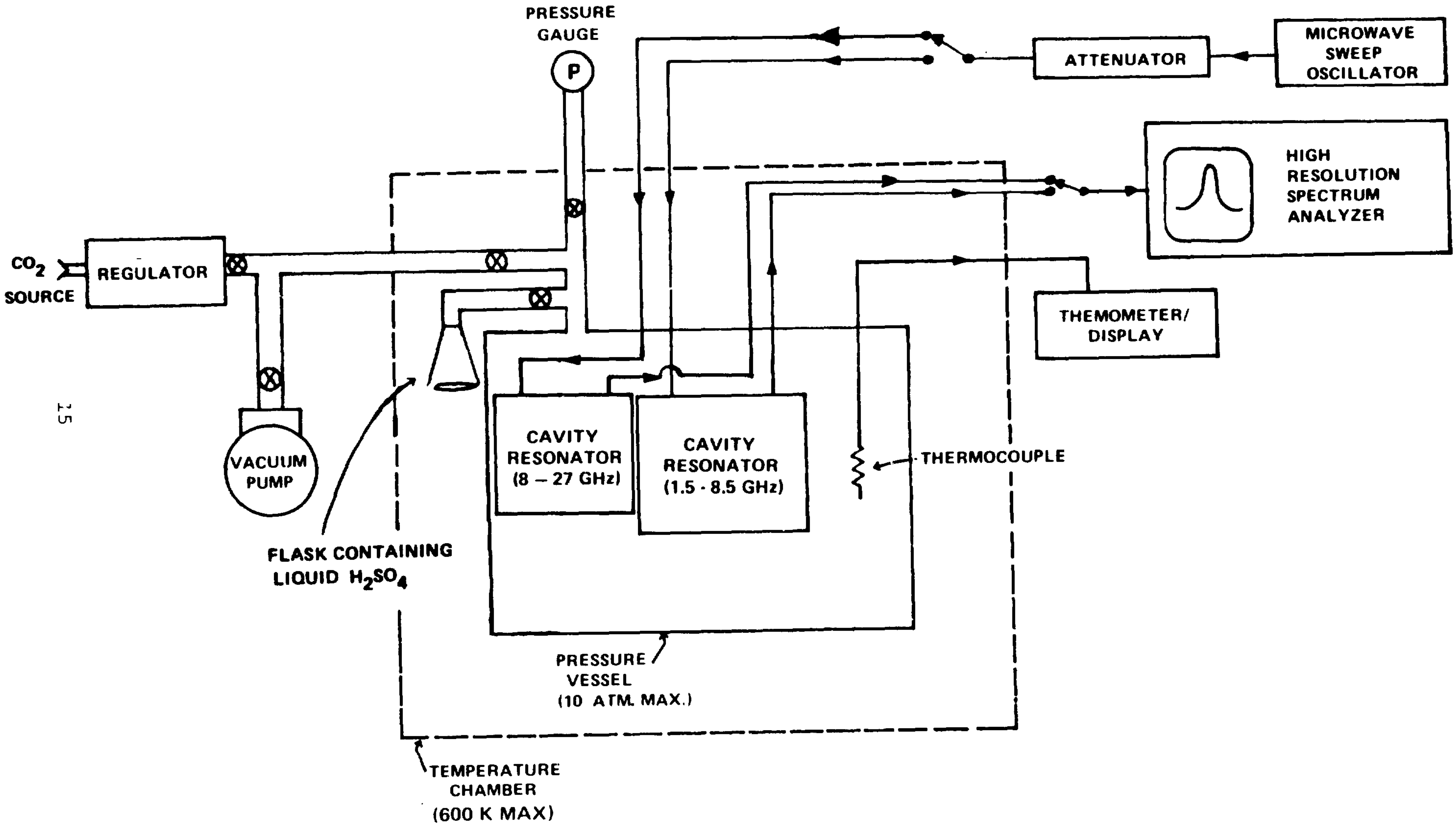

Figure 1: Blockdiagram of updated Georgia Tech Planetary Atmospheres Simulator, as configured for measurements of the microwave properties of gaseous H_2SO_4 under simulated conditions for the Venus atmosphere over the 1 to 20 cm wavelength range.

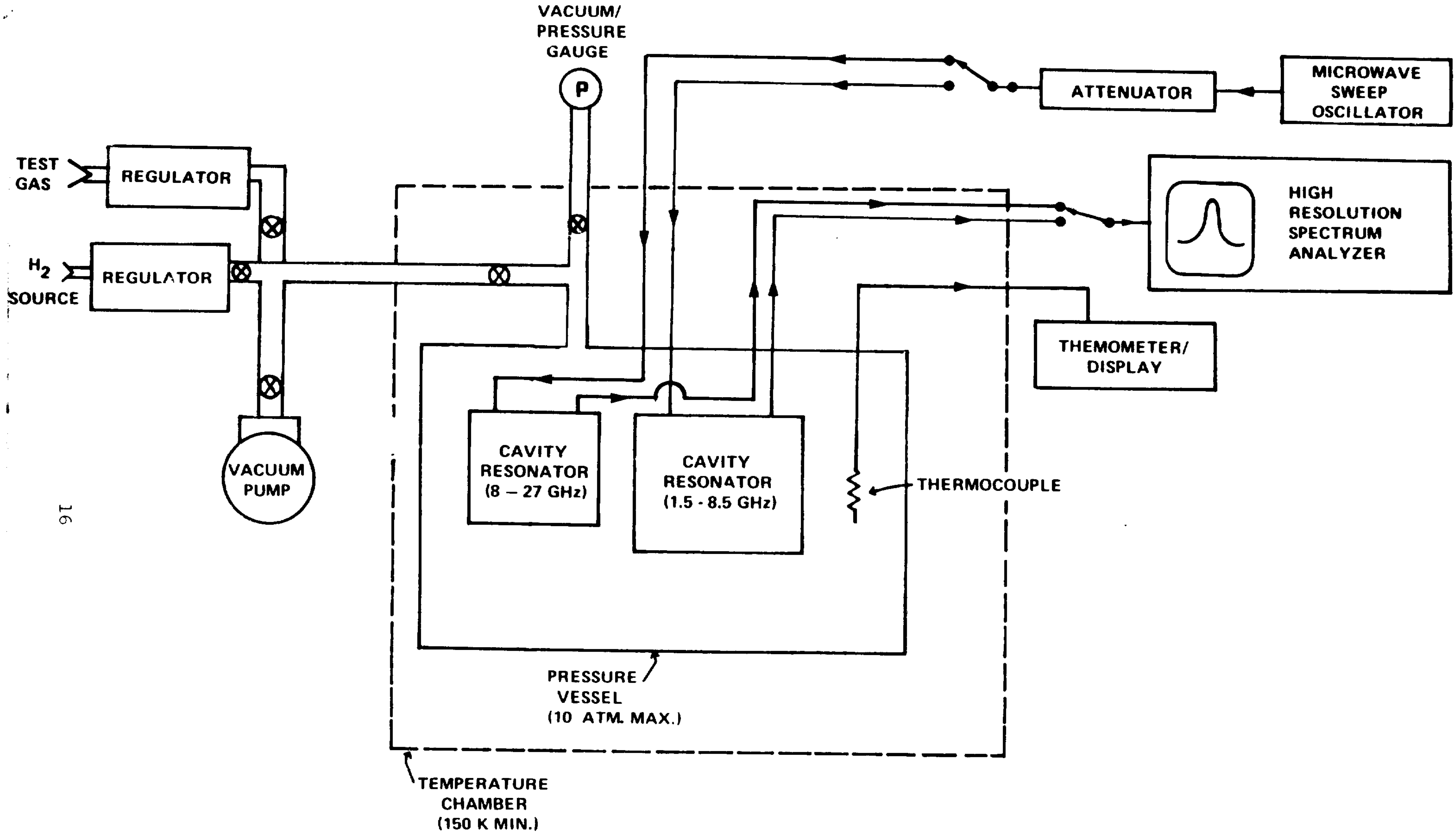

Figure 2: Block diagram of Georgia Tech Planetary Atmospheres Simulator, as configured for measurements of microwave refraction and absorption of gases under simulated conditions for the outer planets.

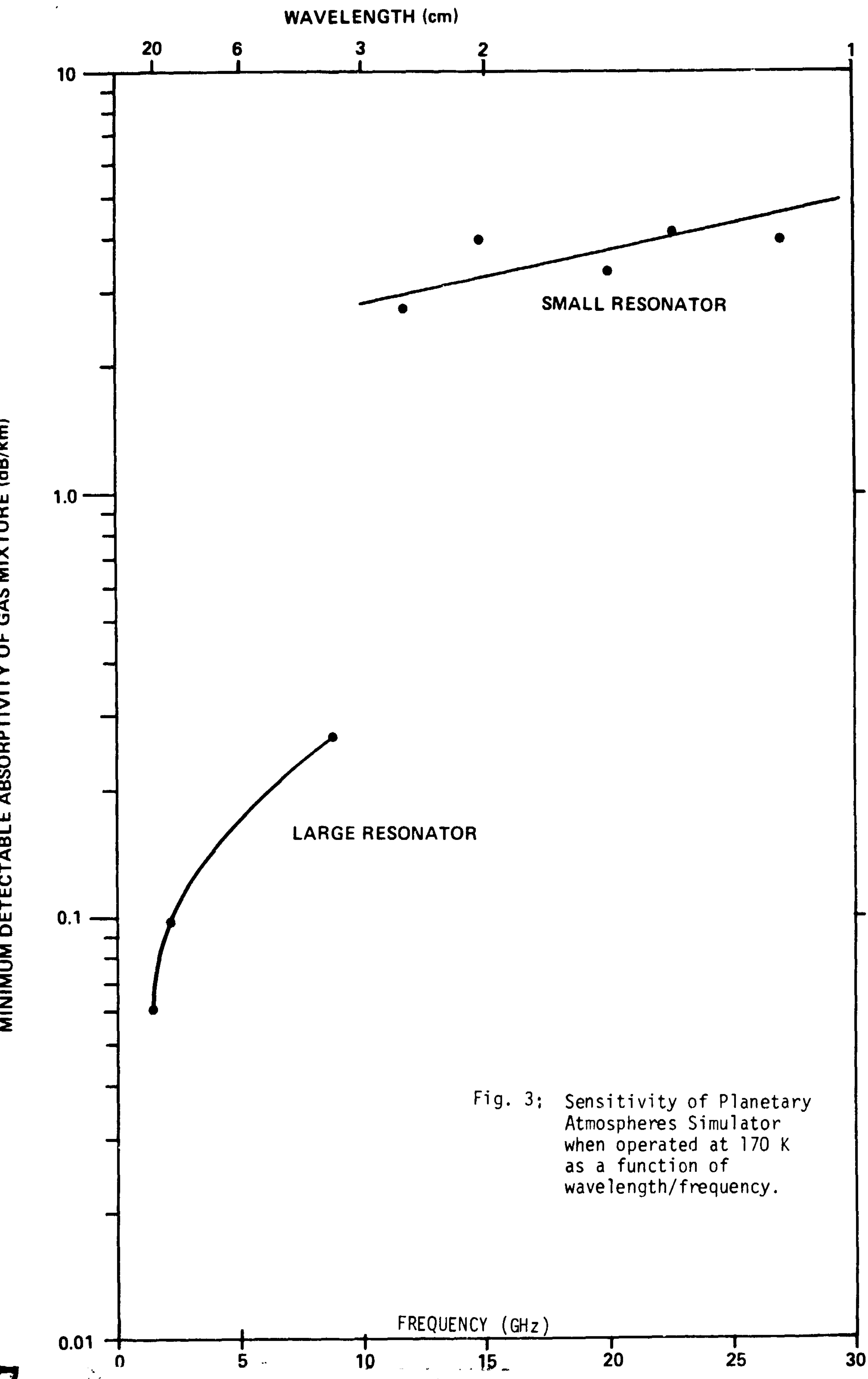

Fig. 3: Sensitivity of Planetary Atmospheres Simulator when operated at 170 K as a function of wavelength/frequency.

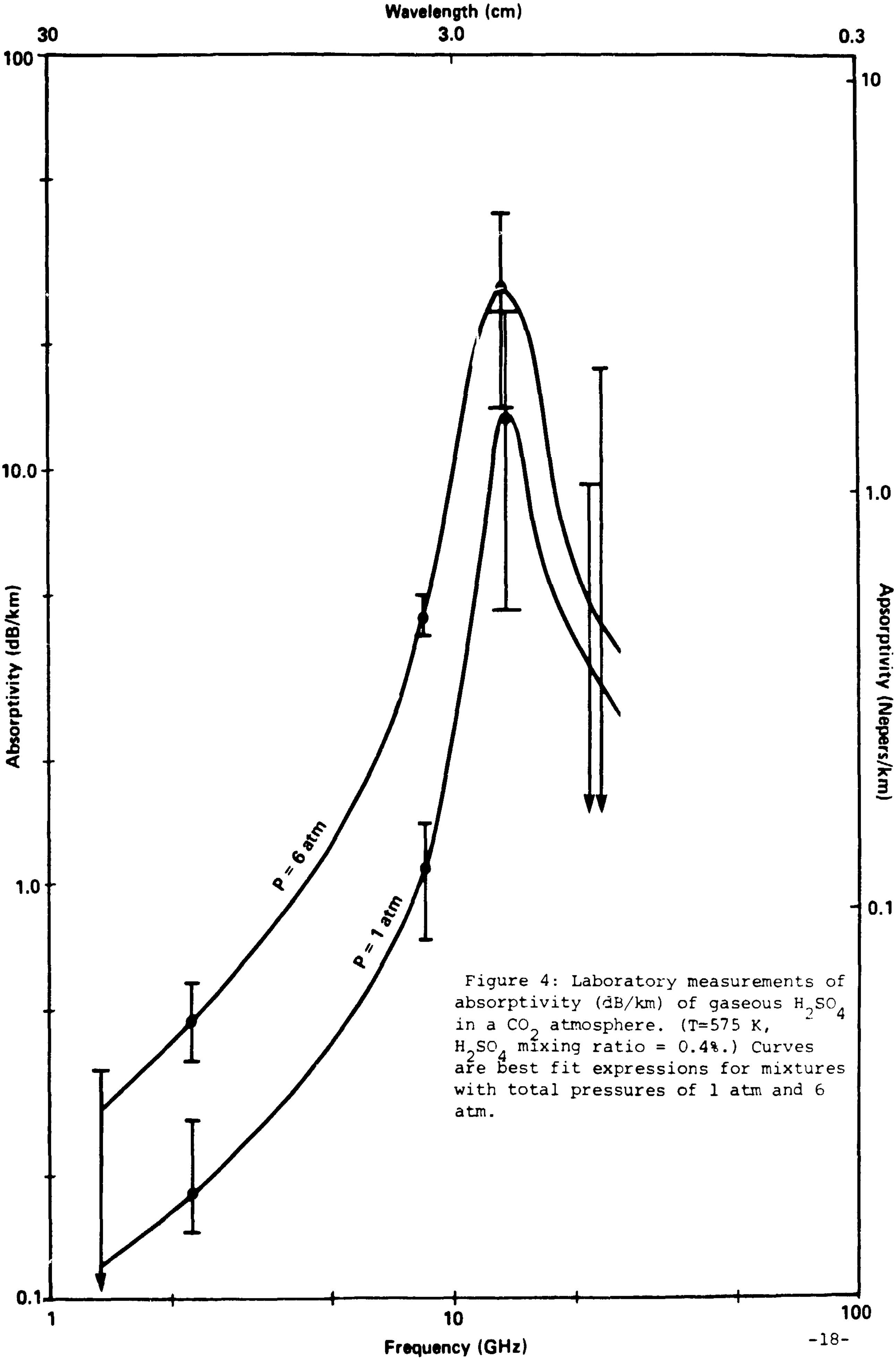

Figure 4: Laboratory measurements of absorptivity (dB/km) of gaseous H_2SO_4 in a CO_2 atmosphere. (T=575 K, H_2SO_4 mixing ratio = 0.4%.) Curves are best fit expressions for mixtures with total pressures of 1 atm and 6 atm.

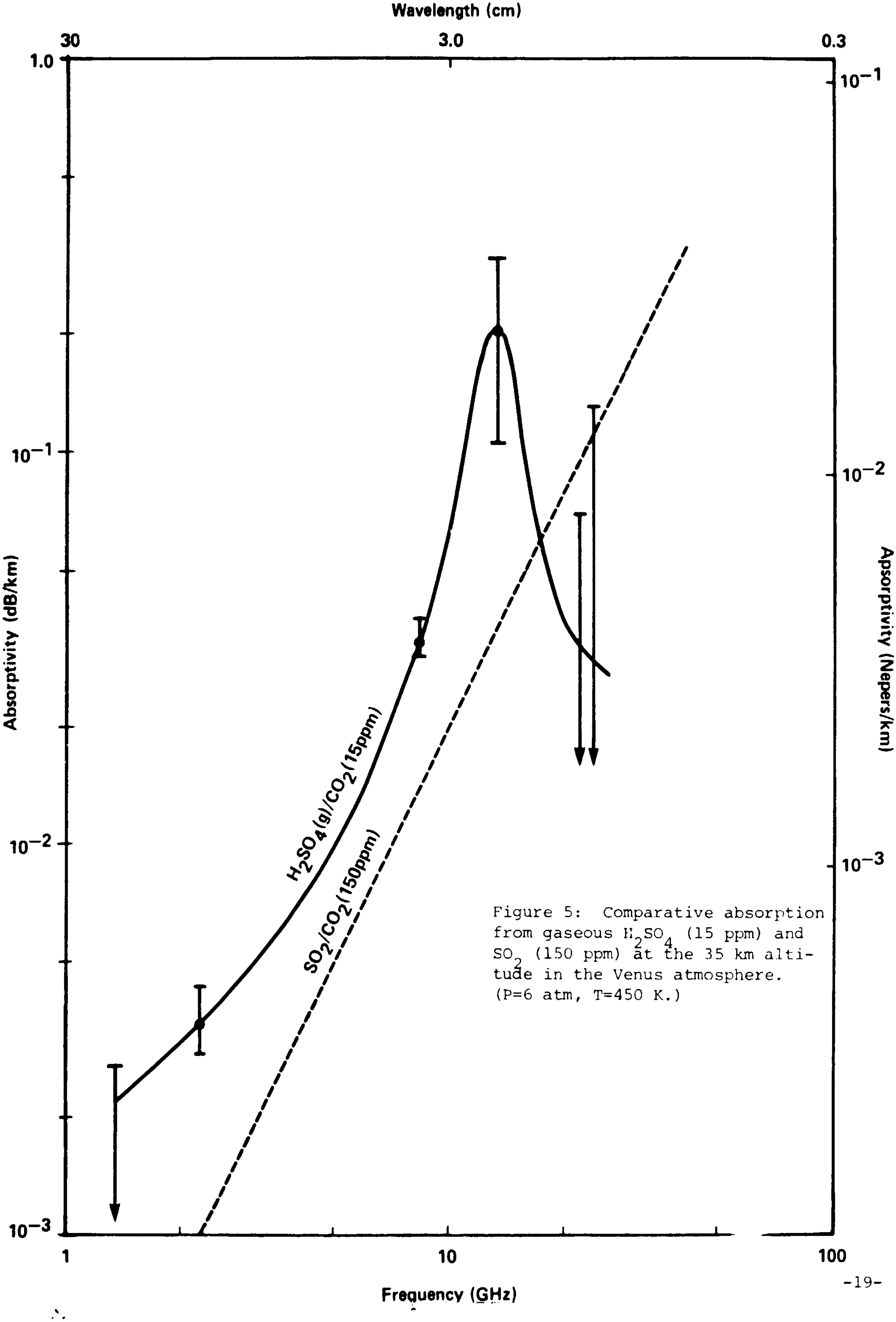

Figure 5: Comparative absorption from gaseous H_2SO_4 (15 ppm) and SO_2 (150 ppm) at the 35 km altitude in the Venus atmosphere. (P=6 atm, T=450 K.)

TABLE I

MINIMUM GASEOUS ABUNDANCES NECESSARY SO AS TO BE MEASURABLE BY THE SYSTEM

Constituent Gas	Abundance of Gas in H_2 atmosphere (6 atm total pressure) required so as to measure microwave absorption at lowest Temperature	Partial Pressure of Gas (in atm.) required so as to exhibit detectable absorption in H_2 atmosphere. (P_{H_2} = 6 atm.)	Lowest Possible Temperature for which required abundance can be achieved (K)
NH_3	60 ppm	3.6×10^{-4}	155
H_2-H_2 and H_2-He* (collisional)	80% H_2 : 20% He	6	20
CH_4**	33%	2	120
CO	Not Detectable in the 1 to 20 cm range by this system		

* Will provide baseline reference for measurements of other constituents

** The theoretically predicted absorption for methane under these conditions is approximately 80% below the minimum detectable absorption for the system. However, it was felt that this is the largest mixing ratio for which hydrogen broadening would still predominate.

VIII. APPENDICES

APPENDIX I : Abstract of paper presented at the Conference on the Jovian Atmospheres (Goddard Institute for Space Studies, New York City, May 1985.)

Laboratory Measurements of Microwave Absorption from Gaseous Atmospheric Constituents under Conditions for the Outer Planets

P. Steffes (Georgia Institute of Technology)

Quite often, the interpretive work on the microwave and millimeter-wave absorption profiles, which are inferred from radio occultation measurements or radio astronomical observations of the outer planets, employs theoretically-derived absorption coefficients to account for contributions to the observed opacity from gaseous constituents. Variations of the actual absorption coefficients from those which are theoretically-derived, especially under the environmental conditions characteristic of the outer planets, can result in significant errors in the inferred abundances of the absorbing constituents. The recognition of the need to make laboratory measurements of the absorptivity of gases such as NH_3, CH_4, and H_2O in a predominantly H_2 atmosphere, under temperature and pressure conditions simulating the outer planets' atmospheres, and at wavelengths corresponding to both radio occultation and radio astronomical observations, has led to the development of a facility capable of making such measurements at Georgia Tech. We describe the laboratory measurement system, the measurement techniques, and the proposed experimental regimen for Summer 1985; with the goal of obtaining feedback from interested investigators on the relative priorities of the various proposed measurements to be made on specific constituents at specific wavelengths.

APPENDIX II:

United States Senate

COMMITTEE ON APPROPRIATIONS
WASHINGTON, DC 20510

May 30, 1985

Professor Paul G. Steffes
Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

Dear Professor Steffes:

Thank you for contacting me concerning NASA.

I believe that the exploration of space and the utilization of knowledge gained from such efforts would prove to be of inestimable value to all people. It is important that we proceed with the development of space exploration technology and I will support such efforts in the Congress.

Again, thank you for contacting me.

Sincerely,

Mack Mattingly

Mack Mattingly

MM/jbh

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AMERICAN ASTRONOMICAL SOCIETY SPECIAL ABSTRACT FORM

Constraints on Constituent Abundances in the Venus Atmosphere from the Microwave Emission Spectrum in the 1 to 20 cm Wavelength Range

P. G. Steffes, D. H. Watson (Georgia Institute of Technology)

We have recently completed laboratory measurements of the microwave opacity of gaseous H_2SO_4 under simulated conditions for the Venus atmosphere in the 1 to 20 cm wavelength range. These measurements, when combined with previous laboratory measurements of the absorption properties of CO_2 and SO_2 in this wavelength range, are used to develop new limits on constituent abundances, based on the observed microwave emission from Venus. We also discuss limits on the long term variations of SO_2 and gaseous H_2SO_4 abundances in the Venus atmosphere, based on the results of the laboratory measurements, and on the reported variations of the Venus microwave emission spectrum.

American Astronomical Society

Date Submitted ____________

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